NOAA Long-Term Research Program Plan

Revolutionizing Tornado Warnings: Phased Array Radar

12 March 2003

A. PROJECT SUMMARY

1. Statement of Objectives

This research initiative attacks the problem of how to improve the lead-times for severe weather warnings including thunderstorms, tornadoes and flash floods. The primary tool for early warnings is the weather radar. Over the last two decades with the implementation of Doppler capabilities, the weather radar has helped improve warning lead times from near zero to greater than 10 minutes on average for tornadoes. NOAA's goal is to increase theses lead times.

The goal of this research initiative is to investigate the use of new technology, in the form of phased array antennas, in weather radars to improve our timeliness of detection by a factor of ten. Along with investigation of other technologies, this could lead to an improvement in lead times of 10 to 12 minutes.

By collecting complete volume scans of data in less than a minute, researchers will be provided more detail on the internal wind field in storms. This data could lead to improved understanding of severe storms and provide new conceptual and computer models of storm evolution. These new insights could then lead to additional warning lead-time improvements.

Phased array radars are currently very expensive. Thus, a special focus is required by the research community to begin to investigate phased array technology as it applies to severe storm detection. The National Oceanic and Atmospheric Administration's Office of Oceanic and Atmospheric Research (OAR) and OAR's National Severe Storms Laboratory (NSSL) in collaboration with the Navy's Office of Naval Research, University of Oklahoma, Oklahoma State Board of Regents for Higher Education, Lockheed Martin, Federal Aviation Administration and Basic Commerce Industries have started an effort to test phased array technology as a part of a weather radar as well as a multi-use radar for tracking aircraft and wind profiling.

There are several compelling reasons why this is the time for this effort.

1. A phased array radar system is being built at the NSSL and NOAA should take advantage of this excellent research tool to learn all it can on improving our ability to provide warnings and forecasts of severe weather in a timely manner.

2. The WSR-88D antenna and pedestal system will have achieved their life expectancy by 2014. Decisions on a replacement antenna should be based on sound

research using the best technology we can afford that improves our ability to improve our severe storm warning lead times.

3. Our understanding of severe storm processes are improving, but we lack the ability to look at lots of fine scale wind fields in the storms to verify or refute various hypothesis concerning tornado formation and hydrometeor distributions. These are key ingredients for improving models and our forecast capabilities.

The NWS/OAR STIP process laid out the requirements for improving the lead-time, probability of detection, and reduced false alarm ratio for tornadoes over the next 5-10 years. This initiative helps NOAA meet those goals.

2. Requirements

Obtaining faster snap shots of the atmosphere requires new technology above and beyond our current weather radar systems. This initiative provides the research required to evaluate new technologies and to obtain those faster snapshots. The new weather radar system must include:

1. Faster volume scanning capabilities.

The detection and warning of tornadoes depends on the evaluation of radar volumetric data currently obtained every 5 to 6 minutes. Critical decisions to issue a warning require confirmation of signatures in consecutive volume scans. Obtaining volumetric data faster will decrease the latency loss in lead-time. Fine scale, in time and space, will provide improved insight into internal storm wind fields. These fine scale data provide the truth data for various hypotheses on how storms develop and form tornadoes.

2. Dual-Polarization.

Improving our precipitation estimates and mapping hydrometeors requires dual polarization capabilities. A phased array dual polarized radar will allow for the rapid mapping of hydrometeors required for improving the microphysics in cloud and storm scale models. Determination of tornado touch down has been shown as possible using the fields of polarimetric variables (Ryzhkov et.al., 2002).

3. Adaptive scanning capabilities.

Tornadoes can be detected from signatures in the Doppler spectra (Zrnic and Doviak, 1976). One needs at least two adjacent radials to identify a shear associated with a tornado using the current methods. A valid spectral signature of a tornado can be confined to one radial, thus increasing the detection range from the radar. Spectra processing requires a relatively large amount of pulses that would slow down data acquisition on conventional radar. An agile beam phased array radar can adapt its scan so that spectra can be collected in certain regions of a storm where tornadoes are likely to form. Longer dwell times can be devoted to collecting spectrum and less important regions can be scanned faster.

4. **Multi-use for weather, aircraft tracking and wind profiling.**
Phased array technology is currently very expensive, although the costs are projected to much less in several years. By providing a multi-use radar that can provide not only weather information, but also track aircraft and provide wind profiles, the phased array radar becomes more affordable, even if reduced costs make it cost effective as a weather radar only.

3. Methods

This initiative will support research and development activities through broadened participation of the research community in evaluating new technology, like phased array radars, and their applications to improving the warning and forecasting of severe storms especially tornadoes. Research will be performed using the new National Weather Radar Testbed (Phased Array) at the NSSL. In addition, new mobile shortwave length non-agile and agile beam systems will be built and tested to evaluate improvements in detection of tornadoes. Using the current weather radar systems, along with the NSSL research dual-polarized WSR-88D, researchers will be able to quantify improvements in the detection of severe storms and especially tornadoes.

This research is required in order to make informed decisions on future improvements to weather radars that will allow for improved detection capabilities leading to improved warnings and forecasts of severe storms.

4. Merit

This initiative uses both research and operational performance measures. The operational performance measures for tornado warning lead-time, probability of detection (POD), and false alarm rate (FAR) comes from the OAR/NWS Science and Technology Infusion Plan (STIP). The STIP identifies a lead-time goal of 18 minutes by 2012 (80% improvement over current levels). The POD and FAR goals are 78% and 64% respectively. The research performance goal is for 45-minute lead-time by 2025 with an 80% POD and 50% FAR. To achieve these goals will require addressing the first three requirements. Investment in long-term research is required to meet these goals.

5. Impacts

NOAA issues official forecast and warnings of tornadoes for the United States. Among the warning quantities critical to public safety and the national economy are tornado lead-time, probability of detection and false alarm rate. Lead times are directly related to saving lives and protecting property (Brooks and Doswell, 2002). The improved detection of tornadoes also leads to improved warnings. Reducing the false alarm rate leads to better confidence in the warning and eliminates the "crying wolf" syndrome. Improvements in tornado forecasting and warning will benefit society. These forecasts and warnings are critical to decision makers such as the emergency managers at the local, state and national level who are responsible for the well being of millions of people and assets worth billions of dollars.

B. Table of Contents

C. Science Plan

1. Introduction

This initiative addresses NOAA's Strategic Plan Mission Goal 3 to serve society's needs for weather and water information. It is a plan for NOAA over ten years (2005-2114) to develop new technology that would *improve effectiveness of observing systems.* The improvements will consist of a) increased accuracy and amount of lead time of tornado detection, b) better detection of flash floods, c) classification of precipitation type including better detection of hail, and d) improved measurement of precipitation. Ultimately these capabilities will advance the accuracy of an operational weather prediction suite.

The proposed new technology is a polarimetric agile beam phased array radar. This radar system will be suitable for multiple mission objectives including those of the Federal Aviation Administration (FAA), Department of Defense (DOD) and Home Land Security. The radar will include new adaptive scanning strategies whereby the regions of most interest (hot spots for tornado spawning, flash flood production, hail generation) would be thoroughly scrutinized while regions of benign weather will still be surveyed. At the same time the radar could track cooperative and non-cooperative aircraft. All this will be done at volume update rates five to ten times faster than the current weather surveillance radars. This technology will include assimilation of radar data into schemes for determination of vector winds required for short-term storm prediction models.

In partnership with the NAVY, FAA, Lockheed-Martin Corp., Oklahoma State Board of Regents for Higher Education, the University of Oklahoma and Basic Commerce Industries, Inc., NOAA is exploring use of agile beam phased array technology. It has obtained an agile beam Phased Array Radar (PAR) and experimental investigation of advantages (appendix) for observing weather will start in summer of 2003. Part of this proposal addresses modifications (operation with two frequencies and pulse compression) of the PAR to allow for very fast volume updates.

The thrust of the proposal is work toward prototype polarimetric phased array radar. We plan to start with a small agile beam phased array, test it on the existing subsystem of the PAR, and eventually develop a full size prototype.

Further it is proposed to develop and test a short wavelength (3 cm) mobile radar. This radar will also have a phased array antenna and dual polarization. It will serve two purposes. One, to be a test bed for a network of gap filling inexpensive radars, and two, to provide rapid polarimetric data for better understanding precipitation processes.

The National Academies Committee on Weather Radar Technology Beyond NEXRAD, recommended that the two complimentary options, agile beam phased array and short wavelength radar network be considered as strong candidates for further scrutiny (NA 2002).

2. Current practices

Detection of vortices - operational

A significant step for detecting vortices occurred after the deployment of the WSR-88D network as can be seen by the abrupt increase in mean tornado lead time from about 7 min to over 10 min (Fig. 1). Two operational algorithms exist on these radars for identifying vortices in the fields of Doppler velocities. The mesocyclone algorithm associates localized (in azimuth and range) chunks of Doppler velocities that increase with azimuth (Lee and White 1998, Stumpf et al. 1998). Continuity in time and height are used as well as criteria about the size of rotating core, maximum shear, and others to separate mesocyclones from transient or benign shears. The tornado vortex algorithm (based on Tornado Vortex Signature – TVS) is similar except is searches for strong localized shears between two adjacent radials (Mitchell et al. 1998).

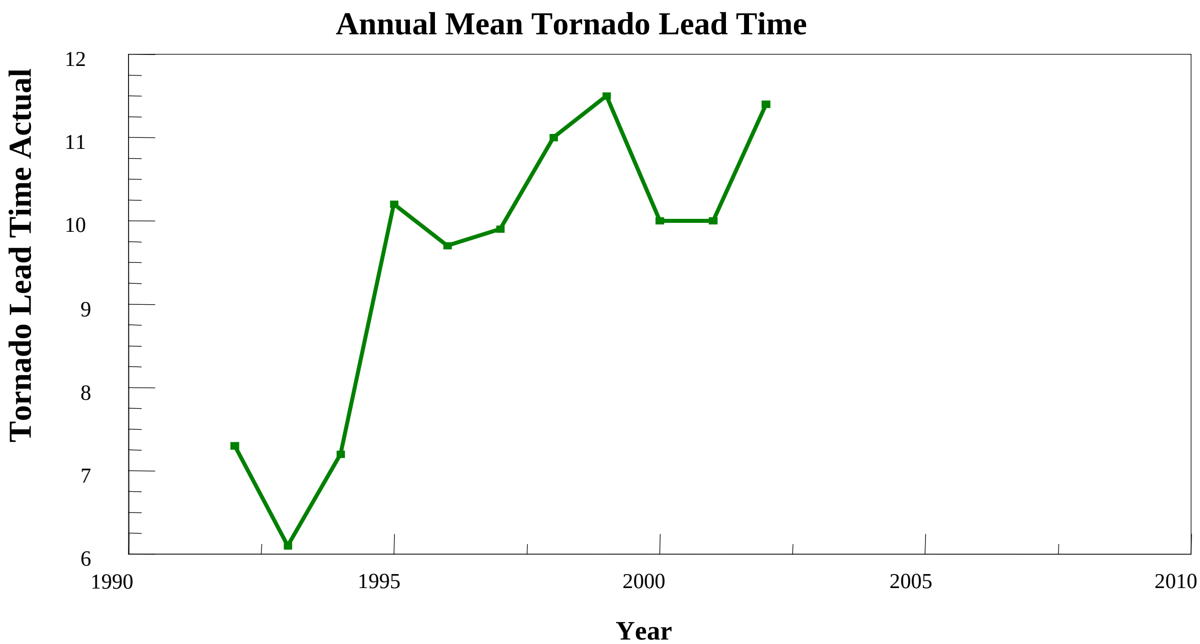

Fig. 1. Tornado lead-time (min) from 1994 until present.

Whether tornadoes are detected or missed depends on interplay between the radius of maximum wind, the maximum wind, the transverse dimension of the radar beam, and the pulse depth. Critical for the decision to issue a warning is the confirmation of signature in consecutive volume scans. Because these scans are more than 5 min apart valuable lead-time is lost. *Clearly faster scan time such as offered by phased array radar would decrease this latency loss in lead-time.*

Detection of vortices- state of the art

Tornadoes can also be detected from the signatures in the Doppler spectra, which have a distinct character that sets these apart from other spectra. Spectra are very broad, and if the tornado is centered on the radar beam spectra are bimodal (Zrni• and Doviak 1976). On this, both observations and model agree (Zrni• et al. 1977). We submit that Tornado Spectral Signatures (TSS) will deteriorate much slower with increasing range than do the signatures in the field of mean velocities (the TVS). Whereas one needs at least two adjacent radials to identify shear, a valid spectral signature can be confined along one radial. Thus it just might be possible to increase lead-time for tornado detection. For example if range is the issue; that is, a tornado is far and the gate-to-gate shear (i.e., TVS) is washed out, the spectral signature might reveal its presence. Also, the TVS may indicate a tornado nearby but loose it if it moves beyond its detection range.

To obtain spectra a relatively large number of pulses needs to be transmitted. This slows down the acquisition rate of conventional radar. *An agile beam phased array can adapt its scan so that spectra are collected from direction (regions in storms) where tornadoes are likely to form. Thus longer dwell time is devoted where it is needed while less important regions are scanned faster.*

Doppler spectra are not yet used for detecting tornadoes in an operational setting, and there are no procedures for doing so in real time. With the introduction of the new signal processor on the WSR-88D network (in 2005) the computing capabilities will be sufficient to perform spectral analysis and subsequent detection of tornadoes when a suitable procedure is developed.

Measurement of precipitation – operational

Accurate determination of hydrometeor type is important not only for estimating precipitation amounts and thereby issuing flash flood warnings, but also for wise water resource management, for cloud models (i.e., improving the microphysics in the model), improving tornado detection via discrimination of tornadic debris from meteorological scatterers, and in aviation safety (e.g., aircraft icing problems).

Current operational methods derive precipitation from the reflectivity factor Z and are plagued by myriad of deficiencies inherent to the measurement of power. These are calibration errors, attenuation, effects of anomalous propagation (AP), ground clutter, and beam blocking. Also, variations in the reflectivity factor Z vs. rain and Z vs. snow relations cause biases in precipitation rates and accumulations.

Hail is identified from high values of the reflectivity, an estimate of the liquid in a vertical column over the observation area, and storm structure (Witt et al. 1998).

Polarimetric measurement of precipitation

The polarimetric Doppler radar has emerged as a leading contender for remote classification of precipitation type and quantification of precipitation (Zrni● and Ryzhkov 1999). Polarimetric Quantitative Precipitation Estimation (QPE) was recently identified as a “key” solution to the science and technology “gaps” during the NWS Science and Technology Infusion Process (STIP) for Hydrology, Aviation, Severe Weather, Winter Weather, and the Observations Cross-Cut.

Polarimetry entails probing of precipitation with orthogonal electric fields (Doviak and Zrni● 1993). For example, horizontally and vertically polarized electric fields interact differently with contrasting hydrometeors, such as rain versus hail, to produce identifiable “signatures” in the fields of polarimetric variables that has promise to provide the following benefits:

- improved Quantitative Precipitation Estimation (QPE)
- discrimination of hail from rain, possibly gauge hail size
- identification of areas of contamination by ground clutter, sea clutter, and anomalous propagation
- identification of precipitation type in winter storms (dry/wet snow, sleet, rain)
- improved tornado detection via discrimination of tornadic debris from meteorological scatterers

- identification of biological scatterers (birds, insects) and their effects on the Velocity Azimuth Display (VAD) wind product
- provision of initial conditions and constraints to numerical models for short-term forecast
- identification of aircraft icing conditions

Scientific evidence accumulated at NSSL demonstrating the potential of radar polarimetry has been sufficiently compelling that the NWS has committed to transform its network of Doppler radars into polarimetric Doppler radars starting in 2007.

Currently there are no rapid scan polarimetric weather radars and a significant component of this initiative is to develop an agile beam polarimetric phase array radar. Conceivably and in due time such radar would replace the polarimetric WSR-88D.

3. Evolution of bulk hydrometeors – a case for rapid observation

It is well accepted that enhanced signatures of polarimetric variables could be tied to specific microphysical processes. By signature, we mean a region in a storm wherein a polarimetric variable has a distinctly different value than in its surroundings. So far several types of signatures have been observed. For example structures of specific differential phase K_{dp} (closely approximates liquid water content) and differential reflectivity Z_{dr} (proportional to the mean diameter of rain drops) columnar fields displaced from each other have been reported in Colorado (Hubbert et al. 1998) and Oklahoma storms (Loney et al. 2002). Both references locate shed drops in the region of the enhanced K_{dp} above the melting layer at the western edge of the updraft. *In-situ* measurements imply that the enhancement of K_{dp} is principally due to wet oriented particles > 2 mm in diameter. If these measurements are representative over the radar resolution volume then the K_{dp} "column" is an indirect manifest of the shedding process (i.e., large number of small 1- 2 mm drops shed of hailstones). In observation of ordinary storm, the Z_{dr} and K_{dp} have been collocated (Zrni● et al. 2001). Further the process of upward drop advection and subsequent freezing has been documented for ordinary storms (Bringi et al. 1997). Very little is known about the evolution and advection of polarimetric signatures in supercell storms and squall lines. These of course are caused by the bulk hydrometeors and frequent observation of the signatures could help explain the microphysical processes that lead to these changes. For steady state conditions, the general features of bulk hydrometeors are somewhat known.

Illustrations of Z_{dr} and K_{dp} signatures in a formative stage of a supercell (Figs. 2 and 3) indicate significant changes in the lowest (1 km) level over a 4 min time interval of observation. Z_{dr} enhancement (> 2 dB) is at the storm periphery except for the North side. The broad enhancement vanishes at the height of 2 km but a well-defined column at about X = 10, Y = 40 km (not shown here) persists. The K_{dp} enhancement is centered on the storm (Fig. 3) and it also changes significantly within the 4 minutes between observations. At 2 km height and above, there is only one well-defined column in K_{dp} and it is offset by about 5 km north of the Z_{dr} column.

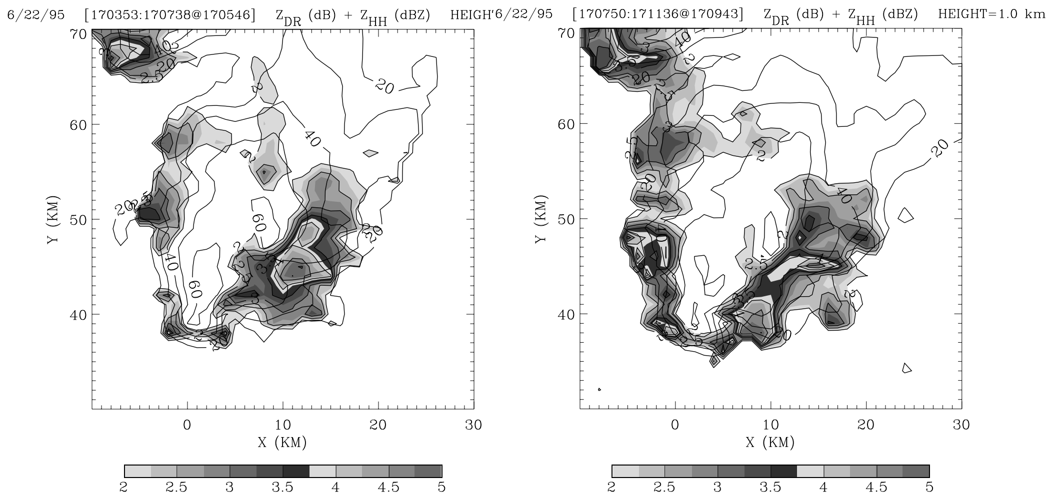

Fig 2. The reflectivity factor field (contours in dBZ) and differential reflectivity field (shaded areas starting at 2 dB; the scale is on the bottom). The storm occurred in Colorado and was observed with the CSU-CHILL radar. Time between scans is 4 minutes.

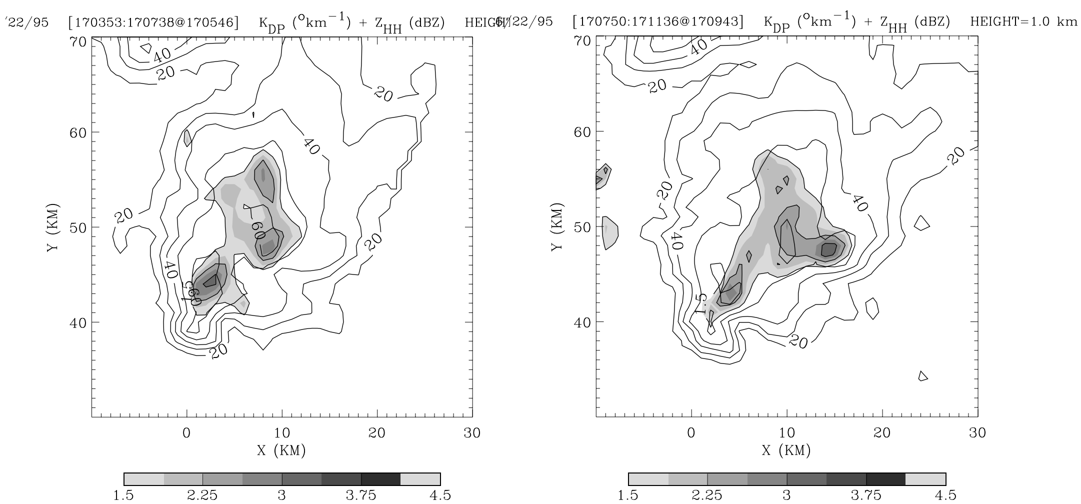

Fig 3. Same as in Fig. 2 except the shaded field is specific differential phase. Depicted are values > 1.5 deg km^{-1}.

In the area of tornado detection rapid polarimetric observations might be extremely beneficial because it has been shown (Ryzhkov et al. 2002) that it is possible to determine the time of tornado touchdown in the fields of polarimetric variables.

We submit that to fully capitalize on polarimetric measurements such as seen in Figs. 2 and 3, we need fast volume scans (< 1 min) and observations with a resolution of few hundred meters. Rapid acquisition of polarimetric data is required for understanding formation and evolution of bulk hydrometeor processes. Scales of these bulk processes occupy a fraction of the generating convective cells and often change very fast. For example drops brought by the updraft into regions cold environment can freeze in about ten seconds.

With the polarimetric phased array radar (mobile X band and the PAR) we plan to obtain signatures at unprecedented update rates and accuracy. Then, time-lapse fields of polarimetric variables will be analyzed to provide information eclipsing the one available from conventional trajectory analysis. The two together might revolutionize the science of bulk hydrometeor microphysics and improve parameterization of precipitation in numerical models.

4. Advantages of the Phased Array for Weather Observation.

In summary the capabilities (advantages) of the agile beam and wide bandwidth radar are as follows.

Fast update rates-
Rapid scan updates enables calculation of crossbeam winds by providing numerical models with accurate and timely data. Frequent measurements of meteorological hazards (e.g., tornado cyclones, hailstorms, etc.) can lead to better warnings and predictions of the trends in these phenomena. Detailed documentation of the life cycle of short-lived features such as vortices, up and down drafts (including microbursts), and turbulent structure of the atmosphere are possible.

Resolution -
Phased arrays provide the best (intrinsic) angular resolution of the beam because there is no smearing due to antenna angular motion.

Better measurements of spectral moments and polarimetric variables in the presence of beam blockage-
The elevation angle of the beam can be programmed to follow the true horizon, say the blockage pattern of ground objects (i.e., buildings, trees, etc.). This allows compensation of the spectral moments and polarimetric variables for the beam blockage effects (Smith and Doviak 1984). Further, the beam is thus positioned at its lowest elevation angle and provides the best rainfall estimates near ground where it matters.

Mitigation of ground clutter effects-
The ground clutter spectrum width is determined only by the motions of the scatterers on the ground and therefore is smaller than what a rotating antenna would measure. This permits more effective ground clutter canceling and better compensation of biases (caused by clutter filtering) in the polarimetric variables and spectrum widths of weather signals. Better recovery of overlaid second trip signals is possible because the ground clutter spectrum occupies a smaller portion of the unambiguous velocity interval.

Instantaneous retrieval of transverse winds-
It may be possible to measure transverse winds using the spaced antenna approach (i.e., by correlating signals received simultaneously on different portions of the phased array (Lataitis and Doviak 1995). This would involve modification of the aperture to gain access to sub arrays.

Simultaneous observation of weather and tracking of objects-
It is possible, while probing a precipitation event, to interleave a sequence of beam positions so that weather characteristics along the path of objects such as aircraft or balloon can be simultaneously obtained with radar and in-situ instruments. This capability would facilitate comparisons of in situ aircraft observations with radar measurements which is significant for microphysical and electrification studies. It is possible to track weather balloons and estimate environmental winds (Zrni•   et al. 1988) while making observations of weather phenomena.

Spectrum width and polarimetric variables measurements-
Because beam smearing is not a factor, the spectrum width estimates of weather signals would have one less bias. Similarly the correlation coefficient between the copolar and cross-polar signals would be less affected. This will improve the quality of spectrum width estimates and would also reduce the standard errors in the Doppler velocity and in the estimates of polarimetric variables.

Reduced maintenance and improved availability
Significant single point of failure in traditional systems is the transmitter. In the PAR transmitter modules are numerous and integrated within the active phase array transmit/receive (T/R) elements. In case of failure of some T/R modules there is a gradual degradation of performance compared to the total loss that occurs in the traditional transmitter.

5. Emerging weather radar technology

Herein are described the technological advances called for in this proposal. That is the deliverables and reasons for these. The main trust is in bringing full capability to the phased array weather surveillance radar while reducing the overall cost. The other important aspect is to explore use of mobile short wavelength phased array radar, which could be a precursor of a network of gap filling instruments.

a. Upgrades on the existing PAR

Facts concerning the forthcoming PAR are as follows:

1. The proof of concept PAR has a 30 year old antenna with bulky and expensive centralized transmit/receive beam-forming system. A considerably smaller, higher performance and less expensive technology are becoming available in the form of active solid-state T/R modules.
2. Transmitter is from a WSR-88D that is rapidly aging. Solid-state upgrade might become available.
3. Pulse compression capability and dual frequency transmission are lacking. These are needed to fully achieve ultra rapid scan.
4. Polarization diversity is not available. This must be implemented to match the future capability of the WSR-88D.

Pulse compression and dual frequency

Two major complementary technological developments make rapid acquisition of weather radar data possible. These are

- Transmission and processing of wide bandwidth signals
- Beam agility of the active phased array radar

With beam agility and adaptive scans the existing PAR could achieve a five-fold increase in the speed of volume coverage. To reach a ten fold increase advanced signal designs and processing are required. Over sampling and whitening of signals in range is a candidate that will be explored (Torres and Zrni• 2003). This technique is effective at large signal to noise ratios. Dual frequency transmission and/or pulse compression can increase the speed of volume coverage without sacrificing signal to noise ratio. Thus the upgrade in the processing area will be activation of a second channel and a pulse compression scheme (Keeler 1994). The frequency in the second channel will be offset from the one in the first channel by 20 MHz. This fits the 40MHz bandwidth of the current analog front-end (including antenna and receivers); it would require a new transmitter, which would be desirable for pulse compression as well. A small compression factor, 2 to 4 is planned so that it could be accomplished within the existing bandwidth of the WSR-88D radars. Simple pulse compression generates range sidelobes that smear (in range) the spectral moment estimates and thus degrade the range resolution. Engineers from Lockheed Martin have developed a Doppler tolerant processing technique to reduce the effect of range sidelobe smearing on the quality of spectral moments (Urkowitz and Bucci 1992). This technique has been implemented and tested on the SPY-1 radar system. Independent tests on the NCAR's ELDORA radar demonstrate that a 7.8 microsecond coded pulse can be used to replicate faithfully spectral moments across reflectivity gradients of 40 dB km^{-1} (Bucci et al. 1997).

Monopulse processing

For tracking aircraft the existing PAR antenna has a monopulse configuration. It is divided into four sub arrays so that the signals from these can be summed and differenced. Currently the sum signals are available, they are "the returned" signals from precipitation. The ports corresponding to the other signals have been terminated. We plan to reactivate these ports to enable tracking of aircraft (NWRT 2001). Thus, considerable hardware and software modifications are proposed.

Solid-state sub array assembly

To demonstrate and evaluate the effectiveness of recent low-cost module approaches and validate their performance and ability to support the goals of improving data quality and effectiveness of weather surveillance systems, we propose to construct a fractional array of 225 elements of a size approximately 1 meter by 1 meter. This fully functional set of modules will function as a small scale solid-state PAR antenna that can be effectively tested at a reduced cost, with the primary restriction being range and beamwidth limitations due to the smaller size of the effective aperture. Critical to this evaluation will be the polarmetric performance of the modules (the long-range weather surveillance radars in the future NWS network must have polarization capability, see sec 3), and the data quality of the resulting sensor system. Ultimately a full-scale pre-prototype antenna will be built and installed in the radar testbed structure for complete evaluation of a full capability PAR surveillance system. Figure 4 illustrates a possible physical implementation of this antenna. This sub-array will serve as proof of concept and will share most of the components (pedestal, transmitter, receiver, processor, display) with the existing PAR.

Fig. 4. Possible physical implementation of sub-array installed on the NWRT.

b. Weather PAR Pre-Prototype

This instrument builds on the existing experience gained from the operation of the PAR and the proof of concept sub array. It is beam agile polarimertric phased array radar. Its characteristics are compatible with the current WSR-88D requirements and volume coverage speed is about 10 times faster than possible today. Its crucial component is the phased array antenna. Modern solid state technology has brought the cost of individual transmit receive (TR) modules to 1/4 of the cost of early solid-state modules in the 1980's.

Active solid-state phased array technology is critical for next-generation military and civilian radars, but historically its cost has been prohibitive. The cost is driven primarily by the large number of expensive solid-state T/R modules required in each array. Achieving significant reductions in module cost will directly benefit both the civil and military radar sectors alike. It will also enable, for the first time, the use of high performance phased array radars for civilian aviation and weather missions, providing significant payoffs in rapid scan for air and weather surveillance.

Recent U.S. Navy programs have demonstrated the application of commercial packaging techniques to RF modules for high-performance phased array radars. Under the Dual Use Science and Technology program, Lockheed Martin demonstrated the effectiveness of industry standard, ball grid array (BGA) technology to make solid-state phased arrays affordable for military and civilian applications. The T/R Linear Replaceable Unit (LRU) drives the performance, cost, and reliability of a solid-state antenna. Recent research has shown that reduction in module and LRU costs can be achieved without sacrificing radar performance.

Conventional, militarized, LRU designs incorporate separate T/R modules, power supplies, control circuitry, etc. enclosed in individual hermetic packages. This approach leads to extremely robust designs and reliable hardware, but at a high cost. To significantly reduce the cost of T/R LRU, we will leverage ongoing research (sponsored by the US Navy and FAA) into a building-block approach similar to those used for PC boards for computers or cellular phones that result in a higher level of integration in the array electronics assemblies.

A key feature of the electronically steerable phased array radar beam is that it can be used to obtain volumetric data with variable spatial and temporal resolutions. Thus, the radar volume will be covered by a constellation of data samples that can be likened to a "hunk of Swiss cheese." Certain regions can be covered by high-resolution data while allowing a relative paucity of data in others. This is in contrast to current operational weather radars, which scan the beam mechanically in a fixed pattern. It is therefore necessary to evaluate whether standard weather processing algorithms are best suited to the phased array radar environment, and, if so, how they should be implemented to best exploit the unique features of this Instrument. Moreover, the variable resolution of phased array meteorological radar data presents new and exciting challenges for display and visualization in both the research and operational settings. The presentation and display of such high-resolution 4-dimenstional data to facilitate assimilation by the human observer is a rich field of research that will only be made possible by these new, and advanced modes of radar operation.

c. Short wavelength mobile phased array

A technology complimentary to the PAR described herein relies on a concept of gap filling of dense network of radars. Inherent to the sparse network (as the WSR-88D) is the degradation of resolution at large distance where the measurements are also made high above ground. Both these impede tornado detection. Measurements of precipitation become suspect because hydrometeors aloft are likely frozen whereas what counts is the accumulation on the ground. In mountainous terrain the beams are often blocked so that precipitation over many valleys is either overshoot by the beam or is totally unrepresentative of the one near ground. These facts were listed in the recent NRC report (NA2002) as major deficiencies requiring new ideas and technology for mitigation. A concept of a dense network of radars is one suggested complement to the existing sparse nodes.

Adding to the uncertainty is the question of frequency allocation for weather radars. The longer wavelength (10 cm) may not be available in the future; hence there is added urgency to examine alternatives. The 3 cm wavelength is a strong candidate for gap filling or dense networks around major populated areas. Addition of polarimetry to the X band radar (Matrosov et al. 2002) has already demonstrated significant improvement for measuring precipitation. Moreover polarimetric measurements can be made with a large unambiguous range so that for purposes of monitoring precipitation there would be no range ambiguous returns. If Doppler velocities are needed, as is the case for tornado detection, the ambiguities at the short wavelength can be prohibitive.

We propose to evaluate the utility of a short mobile X band polarimetric radar. Initially the radar could have a dish antenna. But, our goal is to start with a flat plate polarimetric antenna. It would be a phased array, but without beam agility. It is important that the gap filling radar is very inexpensive and robust, and this technology offers such promise. Nonetheless for resolving rapidly evolving small scale phenomena we will seek as a next step an agile beam phase array antenna.

d. Transition to Operations

The NOAA Research Council has categorized research as short-term, long-term, and research-to-operations. This initiative is long-term research to improve the detection and warning of severe weather. This research will evaluate phased-array technology and short-wavelength mobile systems in support of future needs for the National Weather Service (NWS) operations. The focus is to understand phased Array technology and its application to severe storm detection. Knowledge is then transferred through close collaboration between research and development communities, private sector and NWS operations.

e. Program Management

The NOAA's Radar Research and Development Division (RRDD) of the National Severe Storms Laboratory will administer this program. The phased array radar system is known as the National Weather Radar Testbed (NWRT) and is a national asset that will be managed on a daily basis by RRDD. An advisory board currently meets quarterly to discuss progress, revise goals, and provide guidance to the program. The advisory board consists of NSSL (Kimpel, Zrni● , and Forsyth), ONR (Ferek), University of Oklahoma (Crain, Havlicek, and Shaprio), NWS OST (Saffle), NWS ROC (Belville), Lockheed Martin (McNellis), FAA (Benner and Gordner-Kalani), and BCI (Heimmer and Blasewitz). A National Advisory Panel will be established in the Fall 2005 to review proposals and schedule access to the NWRT. Membership will include NSSL, Office of Naval Research, University of Oklahoma, Federal Aviation Administration, NWS, Lockheed Martin, BCI and the broader research community.

f. Schedule and Interim Milestones

2005
1. Upgrade transmitter with pulse compression and dual frequency capability.
2. Start development of adaptive scan to fine tune interrogation of storms
3. Implement oversampling and whitening
4. Finish design of aircraft tracking enhancements
5. Design dual-polarization sub-array
6. Continue Display and algorithm testing to support phased array radar (i.e. non-sequential, 3-D data stream)

2006
1. Add Aircraft tracking capabilities
2. Construct and add dual-polarization sub-array
3. Evaluate simultaneous collection of weather and aircraft data.

2007 1. Collect initial data on dual-polarization sub-array.
2. Modify displays and algorithms to handle dual-polarized phase array data
3. Evaluate performance of dual-polarized phased array.
4. Develop shortwave length mobile phased array with non-agile beam (SW-MPA-NAB)

2008 1. Continue evaluation of dual-polarized Phased Array data.
2. Collect initial data with SW-MPA-NAB radar

2009 1. Continue evaluation of SW-MPA-NAB radar
2. Design Pre-Prototype dual-polarization phased array radar
3. Add agile beam capability to shortwave length mobile phased array

2010 1. Construct and Add Pre-Prototype dual-polarization phased array radar
2. Evaluate SW-MPA-AB radar

2011 1. Collect initial data with Pre-prototype dual-polarization phased array radar.
2. Modify displays and algorithms to support the pre-prototype
3. Continue evaluation of the SW-MPA-AB radar system

2012 1. Continue evaluation of pre-prototype
2. Make Decision on production of dual-polarization phased array radar

g. Deliverables

A state-of-the-art weather radar. Initial enhancements will allow for fast scanning radar. Enhancements will add dual-polarization and lead to a pre-prototype dual-polarized phase array radar with capabilities to detect weather and aircraft along with providing wind profiles for the initialization of models. In addition, a database of phased array radar data in a variety of weather situations including tornadoes will be provided. Any improvements to our conceptual models of severe weather will be provided to operations along with any suggested scanning strategies for the WSR-88D to optimize severe storm detection. Several mobile shortwave length phased array radars with both non-agile and agile beams. Most research results will be published in the formal literature.

h. Relevance of Work and Synergistic Activities

This initiative would complement and contribute to NOAA's Strategic Plan for 2003-2008 and beyond. It serves society's needs for weather and water information and provides sound, reliable state-of-art research and also contributes to homeland defense and organizational excellence. Furthermore, it helps meet the two corporate practices of effective strategic partnerships and integrated information services.

In addition, this initiative would complement and contribute to the National Weather Service's Science and Technology Infusion Program (STIP) goals of increasing warning lead times for Tornadoes from 10 to 40 minutes in 2025 (see Fig. 5 below taken from STIP briefing by NWS). Phased Array Radar is part of the enabling technologies and would increase our fundamental understanding of tornadoes allowing NOAA to reach this goal.

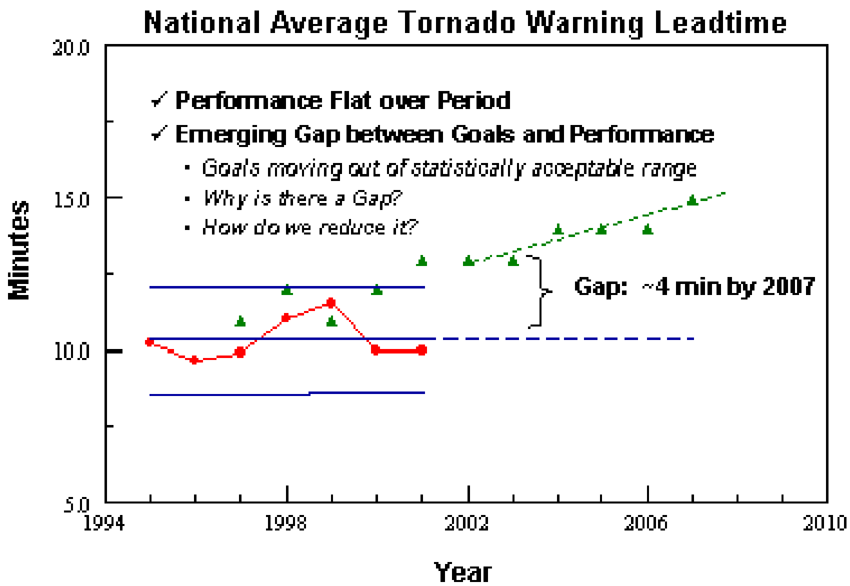

Fig. 5. Average Tornado Warning lead-time current and goal.

The NSSL will continue to work closely in partnership with the Office of Naval Research, University of Oklahoma, Federal Aviation Administration, National Weather Service, Lockheed-Martin and Basic Commerce Industries. Thus, the best of what the Phased Array Radar technology can offer will be applied to weather observations and modeling. This will allow NOAA to improve its lead-time for tornado warnings and improve our ability to track aircraft and weather simultaneously with the same radar system. Other areas of partnership include detection of icing and better initialization of wind data in models.

D. References Cited

Battan, L. J., 1980: Observations of two Colorado thunderstorms by means of a zenith-pointing Doppler radar. *J. Appl. Meteor*., **19**, 580-592.

Bringi, V.N., K. Knupp, A. Detwiler, L.Liu, I.J. Caylor, and R.A. Black, 1997: Evolution of a Florida thunderstorm during the convection and precipitation electrification experiment: the case of 9 August 1991. *Month. Weath. Rev*. **125**, 2131-2160.

Brooks, H.E., and C.A. Doswell III, 2002: Deaths in the 3 May 1999 Oklahoma City tornadoes from a historical perspective. Wea. Forecasting, 17, 354-361.

Bucci, J. N., H. S. Owen, K.A. Woodward, and C.M. Hawes, 1997: Validation of pulse compression techniques for meteorological functions, *IEEE Tr. Geosc. and Remote Sensing*, **35,** 507-523.

Carbone, R.E., B. Foote, M. Moncrieff, T. Gal-Chen, W. Cotton, M. Hjelmfelt, F. Roux, G. Heymsfield, and E. Brandes., 1990: Convective dynamics: Panel Report. Chapter 24b of Radar in Meteorology, (Ed. David Atlas). American Meteorological Society, 391-400.

Carbone R.E. and M.J. Carpenter, 1983: Rapid scan Doppler radar development considerations part I: Sampling requirements in convective storms, Preprints 21st Conference on Radar meteorology, AMS, Boston MA, pp 278-283.

Carbone, R.E., M.J. Carpenter, and C.D. Burghart, 1985: Doppler radar sampling limitations in convective storms, *Jour. Oceanic and Atmos. Tech*., **2,** 357-361.

Crook, A., 1994: Numerical simulations initialized with radar-derived winds. Part I: Simulated data experiments. *Mon. Wea. Rev.*, **122**, 1189-1203.

Crook, A., and J.D. Tuttle, 1994: Numerical simulations initialized with radar-derived winds. Part II: Forecasts of three gust-front cases. *Mon. Wea. Rev*., **122**, 1204-1217.

Doviak, R.J., and C.T. Jobson, 1979: Dual-Doppler radar observations of clear air wind turbations in the planetary boundary layer. *J. Geophys. Res.*, **84**, 697-702.

Doviak, R.J. and D.S. Zrni● , 1993: Doppler radar and weather observations, Academic Press, Orlando, FL p 562.

Feasibility of Tracking Weather and Aircraft, 2001: NWRT Report # 1 prepared by the Basic Commerce & Industries, Inc., Systems and Software Engineering, Moorestown, New Jersey.

Gal-Chen, T., 1978: A method for the initialization of the anelastic equations: Implications for matching models with observations. *Mon. Wea. Rev.*, **106**, 587-606.

Hane, C. E., and B.C. Scott, 1978: Temperature and pressure perturbations within convective clouds derived from detailed air motion information: Preliminary testing. *Mon. Wea. Rev.*, **106**, 654-661.

Hubbert, J., V.N. Bringi and L.D. Carey, 1998: CSU-CHILL polarimetric measurements from a severe hailstorm in eastern Colorado. *J. Appl. Meteor.*, **37,** 749-775.

Katz S.L. and J.D. Nespor, 1993: Advantages of agile beam radar for meteorological functions for hazardous weather detection, Preprints 26th International Conference on Radar meteorology, Norman, OK, AMS, Boston MA, 396-398.

Keeler R.J. 1994: Pulse Compression waveform analysis for weather radar, COST 75 Weather Radar Systems, International Seminar, Brussels, Belgium, Report EUR 16013 EN, 603-614.

Knight, C.A., and P. Squires, Eds., 1982: *Hailstorms of the Central High Plains. The National Hair Research Experiment*, Vol. 1. National Center for Atmospheric Research in Association with Colorado Associated University Press, 282 pp.

Laroche, S. and I. Zawadzki, 1994: A variational analysis method for the retrieval of three-dimensional wind field from single-Doppler radar data. *J. Atmos. Sci*., **51**, 2664-2682.

Laroche, S. and I. Zawadzki, 1995: Retrievals of horizontal winds from single-Doppler clear air data by methods of cross-correlation and variational analysis. *J. Oceanic Technol*., **12**, 721-738.

Lataitis, R.J., and R.J. Doviak, 1995: Precision of spaced antenna wind estimates, Preprints 27th Conference on Radar Meteorology, Vail CO, AMS Boston, MA, pp 717-719.

Lee R.R. and A. White, 1998: Improvement of the WSR-88D mesocyclone algorithm. *Weather and Forecasting*, 13, 341-351.

Levit, J.J., and K.K. Droegemeier, 1999: A simple diabatic initialization technique for storm-resolving models using NIDS Data. *29th Conf. On Radar Meteorology¸* Montreal, Canada, Amer. Meteor. Soc., Boston (abstract submitted).

Lin, Y., P.S. Ray, and K.W. Johnson, 1993: Initialization of a modeled convective storm using Doppler radar-derived fields. *Mon. Wea. Rev*., **121**, 2757-2775.

Loney, M.L, D. S. Zrni• , J.M. Straka and A.V. Ryhzkov, 2002: Enhanced polarimetric radar signatures above the melting level in a supercell storm. *J. Appl. Meteor.* , **41,** 1179-1194.

Matrosov, S.Y., K.A. Clark, B.E. Martner, A. Tokay, 2002: Measurements of rainfall with polarimetric X-band radar. *J. Appl. Meteor*., **41**, 941 - 952.

Mazur, V, D.S. Zrni● , and W.D. Rust, 1987: Transient changes in Doppler spectra of precipitation associated with lightning, *Jour. Geoph. Res*., **92,** 6699-6704.

Mitchell, E.D., S.V. Vasiloff, G.J. Stumpf, A. Witt, M.D. Eilts, J.T. Johnson, and K.W. Thomas, 1998: The National Severe Storms Laboratory tornado detection algorithm. *Weather and Forecasting*, 13, 352-366.

Qiu, C.-J., and Q. Xu, 1992: A simple adjoing method of wind analysis for single-Doppler data. *J. Atmos. Oceanic Technol*.,

Rasmussen, E. N., J. M. Straka, D. O. Blanchard, and T. Shepherd, 1999: The Dimmitt, Texas tornadic supercell of 2 June 1995. Part II: Tornadogenesis.

Reinking, R.F., R.J. Doviak, and R.O. Gilmer, 1981: Clear air roll vortices and turbulent motions as detected with an airborne gust probe and dual-Doppler radar. *J. Appl. Meteor.,* **20**, 678-685.

Ryzhkov, A., D. Burgess, D. Zrni● , T. Smith, and S. Giangrande, 2002: Polarimetric analysis of a 3 May 1999 tornado. Preprints, 21st Conference on Severe Local Storms, AMS, San Antonio, TX, 515 - 518

Shapiro, A., K. Brewster, L. Zhao, S. Weygandt, and S. Lazrus, 1996: Initial forecast fields from single-Doppler wind retrieval, thermodynamic retrieval, and ADAS. *11th Conf. On Numerical Weather Prediction*. Norfolk, VA, Amer. Meteor. Soc., 119-121.

Shapiro, A., P. Robinson, and J. Wurman, 2001: Single-Doppler velocity retrievals with rapid-scan radar data. Preprints, 30th International Conference on Radar Meteorology, AMS, Munich, Germany, 194-196.

Shapiro, A., S. Ellis, and J. Shaw, 1995: Single-Doppler velocity retrievals with Phoenix II data: clear air and microburst wind retrievals in the planetary boundary layer. *J. Atmos. Sci.,* **52**, 1265-1287.

Smith, P.L., K.R. Hardy and K.M. Glover, 1974: Applications of radar to meteorological operations and research, *Proceedings IEEE*, 62**,** 724-745.

Smith, S., and R.J. Doviak, 1984: Doppler velocity bias due to beam blockage by ground targets, *Preprints 22nd Conference on Radar Meteorology*, Zurich, SW, AMS, Boston MA 534-537.

Stumpf, G.J., A. Witt, E.D. Mitchell, P. L. Spencer, J.T. Johnson, M.D. Eilts, K.W. Thomas, and D.W. Burgess, 1998: The National Severe Storms Laboratory mesocyclone detection algorithm. *Weather and Forecasting*, **13**, 304-326.

Sun, J., D.W. Flicker, and D.K. Lilly, 1991: Recovery of three-dimensional wind and temperature fields from simulated Doppler radar data. *J. Atmos. Sci.,* **48**, 876-890.

Sun, J., and N.A. Crook, 1994: Wind and thermodynamic retrieval from single-Doppler measurements of a gust front observed during Phoenix II. *Mon. Wea. Rev.,* **122**, 1075-1091.

Torres, S. M., and D. S. Zrni• , 2003: Whitening in range to improve weather radar spectral moment estimates. Part I: Formulation and simulation. Accepted by the *Jour. Atmos. Oceanic Tech*. AMS.

Tuttle, J.D., and G.B. Foote, 1990: Determination of the boundary layer airflow from a single Doppler radar. *J. Atmos. And Oceanic Technol*., **7**, 218-232.

Urkowitz, H. and N. J. Bucci, 1992: Doppler tolerant range sidelobe suppression in pulse compression meteorological radar, *Proc. Int. Geosci. Remote Sensing Symp*. 1992 Houston, TX, May 26-29, 1992, vol. I, pp. 206-208.

Weather Radar Technology Beyond NEXRAD, 2002: Report prepared by the National Research to the Council National Academy of Science, National Academy Press.

Weygandt, S., A. Shapiro, and K.K. Droegemeir, 1995: Adaptation of a single-Doppler velocity retrieval algorithm for use on a adeep-convective storm. *27th Conf. On Radar Meteor*., Vail, CO, Amer. Meteor. Soc., 264-266.

Williams E.R., S.G. Geotis, and A.B. Bhattacharya, 1989: A radar study of the plasma and geometry of lightning, *Jour. Atmos. Scien*., **46,** 1173-1185.

Witt, A., M. D. Eilts, G.J. Stumpf, J.T. Johnson, E.D. Mitchell, and K. W. Thomas, 1998: An enhanced hail detection algorithm for the WSR-88D. *Weather and Forecasting*, 13, 286-303.

Wolfson, M., C.A. Meuse, 1993: Quantifying airport terminal area weather surveillance requirements, Preprints, 26th International Conf. On Radar Meteorology, Norman OK, AMS Boston MA, 47-49.

Xu, Q., C.J. Qiu, and J.-X. Yu, 1994a: Adjoint-method retrievals of low-altitude wind fields from single-Doppler reflectivity measured during Phoenix-II. *J. Atmos. Oceanic Technol*., **11**, 275-288.

Xu, Q., C.J. Qiu, and J.-X. Yu, 1994b: Adjoint-method retrievals of low-altitude wind fields from single-Doppler wind data. *J. Atmos. Oceanic Technol*., **11**, 579-585.

Xu, Q., J. Qiu, H.-D. Gu, and J.-X. Yu, 1995: Simple adjoint retrievals of microburst winds from single-Doppler radar data. *Mon. Wea. Rev*., **123**, 1822-1833.

Zhang, J., and T. Gal-Chen, 1996: Single-Doppler wind retrieval in the moving frame of reference. *J. Atmos. Sci*. **53**, 2609-2623.

Zrni● , D.S., D. Sirmans, and E. Kessler, 1988: Determination of winds from balloon tracking with a Doppler weather radar, *Jour. Oceanic and Atmos. Tech.*, **5,** 442-449.

Zrni● D. S. and A. V. Ryzhkov, 1999: Polarimetry for weather surveillance radars. *Bull. Amer. Meteor. Soc.*, **80**, 389-406.

Zrni● , D.S., W.D. Rust, and W.L. Taylor, 1982: Doppler Radar Echoes of Lightning and Precipitation at Vertical Incidence, *J. Geophy. Res*., **87**, pp. 7l79-7l9l.

Zrni● , D.S. and R.J. Doviak, 1976: Velocity spectra of vortices scanned with a pulsed-Doppler radar. *Jour, Appl. Meteor*. 14, 1531-1539.

Zrni● , D.S., A.V. Ryzhkov, J.M. Straka, Y. Liu, and J. Vivekanandan 2001: Testing a procedure for automatic classification of hydrometeor types. *J. Atmos. Oceanic Tech*., **18**, 892-913.

Zrni● , D.S., R.J. Doviak, and D.W. Burgess, 1977: Probing tornadoes with a pulse Doppler radar. *Quart. J. R. Met. Soc*., **103**, 707-720.

E. Proposal Budget

1. Cumulative Budget

2005 - 2012: Average of $10.5M/year, where $3.0 M is for phased array infrastructure including $1.2M for staff beyond base: NSSL (6 staff-years), plus $3.0M for Phased array R & D including $2M for staff beyond base: NSSL (10 staff-years), plus $14M to add dual-polarization capability in the 2005-2007 timeframe, plus $25M to add the pre-prototype antenna in the 2009-2012 timeframe, plus $0.275M for travel, workshops, and coordination meetings, and an estimate of $1.4M for spares upgrades, operating and computer costs and $1.1M for non-NSSL support (i.e. Universities, other NOAA Labs, private contracts, etc.)

This assumes 1 Staff year = $200K for salary, overhead, and infrastructural needs.

2. Annual Budget

	Year	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12
RESEARCH											
PAR Infra			1.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
PAR R&D				3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
HARDWARE											
Acquistion	29.8										
Upgrades				2.0	10.0	2.0	0.0	2.0	10.0	10.0	3.0
TOTAL	29.8	0.0	1.0	8.0	16.0	8.0	6.0	8.0	16.0	16.0	9.0

3. Justification

For Phased Array Radar infrastructure, there will need to be two technicians, one engineer along with three system analysts to support and maintain the Phased Array radar. In addition, spares and minor upgrades (i.e. Transmitter, etc) will average $300K per year. Operating costs will average $50K per year for Air Conditioning, Electrical and etc. Expertise for maintaining this complex facility will require an external contract amounting to $300K per year. The digital signal processor will have to be increased at an average cost of $100K per year. The networking support and computer maintenance costs will average $50K per year. Approximately, $900K per year will be used to develop the short wavelength mobile phased array radar. Travel is estimated at $100K per year.

For Phased Array Radar Research and Development, there will be the need for 10 scientists and system analysts working on the radar to analyze the data and to improve the radar operations and displays. Three- and 4-Dimensional displays will be required to visualize the data along with improved workstations for the scientists to perform their analysis at a cost of $25K per year. Four non-NOAA scientists with students will contribute to the analysis of data at a cost of $800K per year. Travel, workshops, coordination and National Advisory Panel meetings will cost an average of $175K per year.

The first major upgrade will provide a dual-polarized sub-array starting in 2005 and implemented in 2007 at a cost of $14M. The second major upgrade will be to build a pre-prototype dual-polarized phased array system at an estimated cost of $25M during the period 2009 to 2012.

F. Current and Pending Support

The National Weather Radar Testbed has been funded by the U.S. Navy, $10M along with $10 for the SPY-1A antenna for a total of $20M. The National Weather Service contributed the transmitter worth $400K. The University of Oklahoma purchased the Environmental Processor from Lockheed Martin with funding from NOAA's Office of Oceanic and Atmospheric Research ($1M), Oklahoma State Regents for Higher Education ($M), Lockheed Martin ($1M in-kind) and the University of Oklahoma ($500K). The Federal Aviation Administration has now invested $8M into the NWRT program. Total investments so far have been $31.9M.

NSSL base funding is $200K.

The President's budget contained $1M for FY03 but this was lost in conference. The President's budget also contains $1M for FY04.

G. Facilities, Equipment, and Other Resources

The NWRT is currently being built at the NSSL and will become operational in August 2003. The Testbed Control Center (TCC) is located in the NSSL's NWRT and Observations facility (NOF). The NWRT consists of a SPY-1A antenna mounted on a rotateable platform along with a WSR-88D transmitter modified to transmit on a frequency of 3.2 GHz. The digital signal processor (EP) is located in the TCC along with the control and display systems.

H. Acknowledgements

This initiative is a group effort with input and comments provided by:

Dusan Zrni•	NSSL
Douglas Forsyth	NSSL
Jeff Kimpel	NSSL
Dick Doviak	NSSL
Joan O'Bannon	NSSL
Dena Grose	NSSL
Ron Ferek	Navy/ONR
Tom McNellis	Lockheed Martin

Jerry Crain	University of Oklahoma
John Heimmer	BCI
Bill Benner	FAA
Nannette Gordner-Kalani	FAA

APPENDIX

Enhanced weather observations with agile beam phased array radar (PAR)

Phased array Doppler radars offer the prospect of routinely sampling the atmosphere with volume scan rates an order of magnitude faster than the fastest (5 min) operational scan mode of the WSR-88D Doppler radars. Access to such high temporal resolution data in real-time would offer immediate and tangible societal benefits through improved hazard-warning (e.g., microburst and mesocyclone detection), nowcasting, and guidance for aviation operations. For example, Wolfson and Meuse (1993) determined that a 1 – minute updates improved lead-times for microburst detection by 2.5 to 3 min. By permitting quantitative analysis of convective phenomena on time scales less than 1 minute, rapid scan Doppler radar would also have a profound and wide-ranging impact on storm- and meso-scale meteorological research, and on research training. The objectives of research with the phased array radar are: a) to explore utility of rapid scan data for numerical storm-scale and mesoscale models; b) to improve understanding of a variety of complex convective phenomena with applications to detection and warning; and c) to evolve (or adapt) this new technology for optimum observations (capture) and display of weather radar information.

In principle such radar can serve multiple purpose, from tracking aircraft and surveying weather in general to deeper probing for tornadoes, microbursts, wing tip vortices or similar small scale hazardous weather phenomena

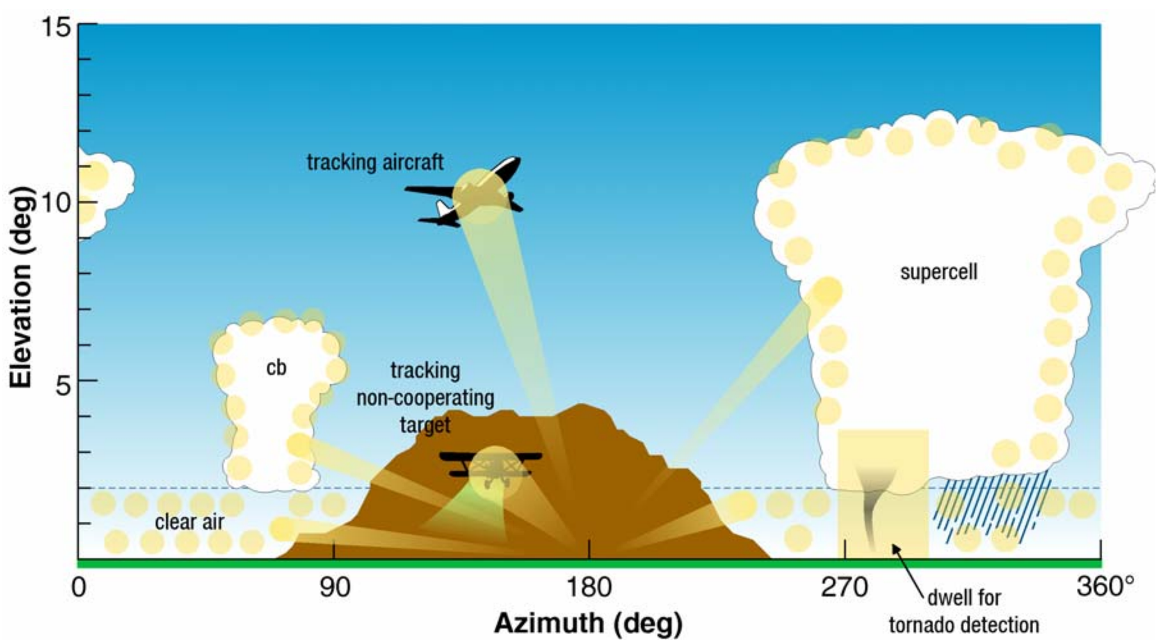

Fig. A.1 Scanning capabilities of agile beam phased array radar. Illustrated are a) surveillance scan through the planetary boundary layer for mapping winds, b) surveillance scan through a cumulonimbus developing cloud, c) surveillance scan through a supercell storm, d) scan with a longer dwell time through a region of potential tornado, and e) tracking commercial aircraft and non cooperating aircraft.

A.1 Numerical Models

A.1.a) Convective Models of actual weather situations require accurate knowledge of wind vectors refreshed at intervals of less than one minute. Carbone and Carpenter (1983) and Carbone et al (1985), found the need for a rapid scan Doppler radar to stem from the high temporal variability of convective elements. Indeed, it has been found that convective structures have large amounts of kinetic energy on spatial scales of 1-2 kilometers and 1-3 minutes (Knight and Squires, 1982; Battan 1980; Carbone et al. panel report, ch 24 of Radar in Met. 1990). Therefore, to properly capture these energy-containing structures, it is desirable to know the wind-speed in at least 2-dimensions and (especially) vertical velocity with data gathered at less than 1-minute intervals. In conventional thermodynamic retrievals (Gal-Chen 1978, Hane and Scott 1978) the pressure field is obtained from the requirement that it satisfy, in a least squares sense, the horizontal equations of motion with the (known) velocity-dependent forcings. The accuracy of the retrieved perturbation pressure (and subsequently the temperature) is tied to the accuracy of local derivatives -- time tendencies -- of the velocity field. Crook (1994) demonstrated the critical importance of time derivative terms in a series of simulated data experiments. His experiments indicated substantial reduction in errors with shorter assimilation windows. Improved wind and thermodynamic field estimates can lead to improved understanding of short time scale mixing processes and complex structures in the atmospheric boundary layer (ABL) (Doviak and Jobson 1979; Reinking et al. 1981; etc), and can potentially lead to improved ABL parameterizations in mesoscale, regional and climate models.

Wind retrieval

A single radar installation can only measure wind speeds along a radial line from the radar. This single Doppler velocity retrieval (SDVR) capability can be used with a number of SDVR techniques to estimate the complete wind vector field when only given the reflectivity and/or radial velocity data. Progress has been made in recent years with full numerical model adjoint algorithms (Sun et al. 1991, Sun and Crook 1994) as well as with simpler algorithms based on radar reflectivity and/or radial velocity conservation principles (Zhang and Gal-Chen 1996; Shapiro et al. 1995; Qiu and Xu 1992; Xu et al. 1994a,b, 1995; Weygandt et al. 1995; Laroche and Zawadzki 1994, 1995; Tuttle and Foote 1990). The retrievals differ in the degree of conservation (strong constraint versus weak constraint) and in the nature of the retrieval domain (horizontal 2-D versus 3-D). They also differ in the nature of additional physical constraints such as spatial smoothness constraints, and mass conservation (applied as a strong constraint, weak constraint or not applied at all). Most importantly, many of these retrievals either make explicit or implicit use of a temporal constraints, for example, velocity stationary, Taylor's frozen turbulence hypothesis, or temporally constant forcing -- constraints whose validity degrade with time. We also note that the success of a simple variational algorithm to estimate the vertical velocity from reflectivity data in simulated convective storms depends critically on the availability of rapidly scanned data (Levit and Droegemeier 1999). A rapid scan radar offers perhaps the best opportunity for these single-Doppler retrievals to perform well with rapidly evolving convective weather phenomena. Recent retrieval experiments with data gathered by the Doppler-on-Wheels (DOW) research radars (described by Shapiro et al. 2001) have focused on the role of temporal resolution. Dual-Doppler analyses were used to verify the cross-beam (azimuthal) velocity component obtained from the retrieval algorithm. The results (Fig. A.2) suggest that a dramatic reduction in RMS error can be achieved as the volume scan times decrease from 5 minutes (characterizing the current WSR-88D scan rates) down to 1 minute (the fastest scan time in the DOW field deployments). The RMS error in the crossbeam wind component (Fig A.2) is for an Oklahoma stationary front on 16 June 2000. The trend suggests that further improvements could be attained with scan rates faster than 1 minute.

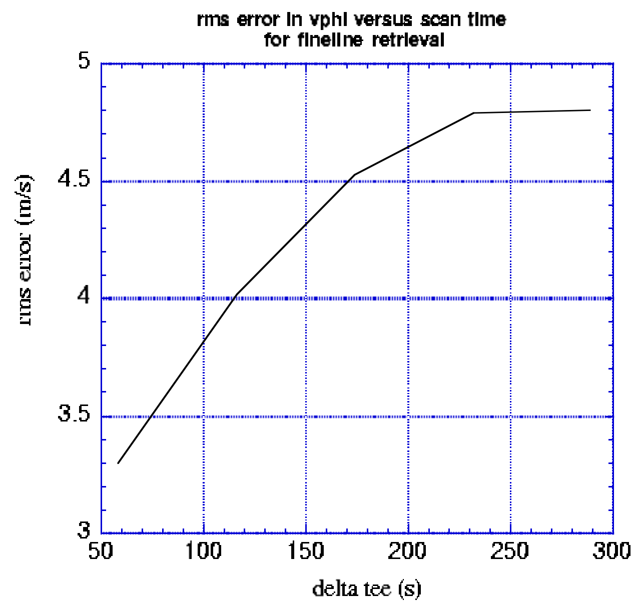

Figure A.2. Root mean square error of transverse wind as a function of time between scans.

A.1.b) Initialization of small and meso-scale numerical prediction models

Convective models used with rapidly updated wind vector data can predict weather instabilities. Single- and multiple-Doppler retrievals and thermodynamic retrievals described above can be used as stand-alone algorithms for diagnostic purposes, hazard warning, and nowcasting. Perhaps the most important application is in the initialization/assimilation of small and meso-scale numerical weather prediction models. Assimilation of clear air boundary layer data in cases where sea breeze fronts, inland sea breeze fronts or boundaries from pre-existing convection are present may also improve the timing and location of convective initiation, a key problem in the numerical prediction of severe weather. In addition, assimilation of radar data and derived fields when convective weather is present can potentially reduce the pervasive "spin-up" problem in numerical weather prediction, that is, reduce the time for model physics to generate convective elements with non-convective background fields. A landmark study in this direction involved the simulation of the 20 May 1977 Del City, OK tornadic storm by Lin et al (1993). In that study, initial forecast fields were prepared with dual-Doppler analyzed winds and an associated thermodynamic retrieval. Discrepancies developed between the observed and simulated storm that were attributed to low update rate. Crook and Tuttle (1994) initialized the dry boundary-layer flow in a numerical prediction model with single-Doppler retrieved winds of gust fronts using the TREC (Tracking Radar Echoes by Correlation) algorithm (Tuttle and Foote 1990) and a thermodynamic retrieval. This procedure resulted in modest improvements over a persistence forecast.

At the Center for Analysis and Prediction of Storms (CAPS), a high-resolution numerical weather prediction model, the Advanced Regional Prediction System (ARPS) and associated Data Analysis System (ADAS) have been developed to improve the prediction of hazardous small-scale weather. This system has the option to assimilate radar data, and wind and thermodynamic fields derived from radar data. The procedure blends crossbeam winds from the Shapiro et al (1995) single-Doppler velocity retrieval with ADAS-analyzed background fields for use in the Gal-Chen (1978) thermodynamic retrieval. The radar data and retrieved variables are then treated as observations in an ADAS re-analysis. A test of this algorithm with NEXRAD data of an Oklahoma squall line on 7 May 1995 clearly suggests the utility of radar data to reduce spin-up time (Shapiro et al. 1996).

A.2) Studies of turbulent storm characteristics and phenomena

Smaller scale, more transient features of convective storm structure are well suited for observations with the phased-array radar. Such aspects as, determination of turret-scale air motions, quantification of entrainment, advective characteristics of charge separation, lightning channel structure, regions of localized convergence, and turbulent flow can be observed with unprecedented temporal resolution. A description of some of these follows.

- ***Vortex dominated flows***

Vortex flows abound in nature and in engineering applications. The smallest of these vortices are generally intermittent and short-lived and include such phenomena as turbulent eddies in dry convection and clouds, aircraft wake vortices, dust devils, Kelvin-Helmholtz billows, waterspouts and tornadoes. The phased array radar is well suited to repetitive rapid observations that, at close range, can detect and provide warning of some of the more hazardous of these vortices. Additionally, phased array radar measurements can potentially aid in the formulation and verification of theories of turbulent mixing in clouds (with implications for precipitation processes), turbulence in rotating structures, dissipation of wake vortices, and perhaps one of the greatest phenomenological mysteries in meteorology – tornadogenesis.

Observations of the Dimmitt, Texas tornado of 2 June 1995 (Rasmussen et al. 1999), with an airborne Doppler radar revealed that the time scale for tornadogenesis was exceedingly small -- the average tangential velocity in the vortex at 700 m radius and 3 km AGL increased from 7.5 m/s to 20.3 m/s in a period of 78 s. These airborne data were collected with a helically scanning tail-mounted antenna using a "fore-aft" scanning technique. The radar fortuitously observed the tornado from one angle while still weak, and then from the other angle while it was intensifying rapidly. Dual-Doppler wind syntheses were only available on each pass of the radar at roughly 7 min time intervals. The rapid evolution, which may typify tornadogenesis, is impossible to observe with conventional scanning radars. To fully document the process of tornadogenesis, volumetric scan times of roughly 20-30 s are required for volumes of order 1x10^2 km^3.

- ***Lightning channels***

Radar observations of lightning channels have a long history. Spatial extent of the lightning echo has been documented with fan beam antennas at different wavelengths. Using vertical pointing antenna it was possible to separate contributions to the Doppler spectrum due to lightning from those of precipitation (Zrnić et al. 1982). This made it possible to infer accelerations of the channel as well as the vertical velocity of air (Mazur et al. 1987). It is now known that, at the 10 cm wavelength, the lightning plasma remains overdense for 10s to 100s of milliseconds (Williams et al. 1989). During this time continuous current flows through the channel. But because the channel branches over large volumes, so far it has not been feasible to map its three-dimensional structure in the fields of Doppler spectral moments. With the wide bandwidth and agile beam steering it should be possible to cover an az-el sector of 8x15 deg in about 100 ms. By working backward in time the precise map of the lightning channel could reveal the location of regions with highest values of electric field where lightning initiates. This could also help determine the influence of electrical fields on the evolution of hydrometeors.

A.3) Phased-array radars provide fastest updates, maximum flexibility.

Present day weather radars use mechanically steered reflector antennas and process a large number of weather signal samples (e.g., 40 to 60 for the WSR-88D) to provide, for each resolution volume, an accurate estimate of spectral moments (i.e., signal power, Doppler velocity, and spectrum width; Doviak and Zrnić, 1993). A large number of echoes are required to reduce the statistical uncertainty of the estimates caused by randomly fluctuating weather signals. The mechanically steered beam limits the speed with which a storm volume can be probed. The PAR (i.e., SPY-1) has electronic beam steering that allows rapid scans.

The beam scanning agility of the phased array system can alleviate the wasteful use of radar resources by employing a visionary scheme proposed by Smith et al. (1974). That is, while the scatterers in one resolution volume are reshuffling into an independent configuration, the phase array radar can switch its beam to another direction to obtain a second pair of samples to estimate spectral moments, and then continue to other directions returning to the original direction after about 5 milliseconds. This beam-multiplexing scheme has been demonstrated on a similar system by engineers at Lockheed Martin (Katz and Nespor 1993).

On the other hand, there are benefits to dwelling along one beam direction and processing correlated samples. For example, spectral distribution of Doppler velocities can be retrieved to estimate maximum radial wind in each resolution volume; this could be useful for estimating maximum winds in tornadoes.

The bulk of meteorological research today is done simply with the first three moments of the Doppler spectrum. The phased-array radar allows more time for data collection in pre-selected regions of interest with minimum sacrifice of volumetric update rates. Thus, locations where tornadoes, microbursts, turrets, or transient features exist can be probed with a long uniform pulse repetition sequence to reveal the distribution of

Doppler velocities. At that there would be little, if any, compromises in the speed at which the spectral moments from the surrounding storm volume are being collected.